ENHANCING THE WEAR RESISTANCE OF Ti-6Al-4V ALLOY THROUGH ELECTRON BEAM ASSISTED OXYGENATION

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Irradiation with a low-energy, high-current electron beam of microsecond duration was shown to substantially enhance the tribological properties of Ti-6Al-4V alloy. Irradiation was carried out in the two modes: at ambient (300 K) and elevated (823 K) temperature. Auger electron spectroscopy showed that irradiation at ambient temperature results in cleaning the surface layer from the dissolved atmosphere gases oxygen and carbon. However, the wear resistance of titanium alloy irradiated at ambient temperature was found to be worse than that for the non-irradiated one. In contrast, a high fraction of oxygen in the surface layer of a specimen irradiated at the elevated temperature was revealed. The high fraction of dissolved oxygen was established to induce the phase transition in the surface layer and occurrence of omega-phase of titanium having the enhanced mechanical properties. The wear resistance of titanium alloy irradiated in this mode is more than fifty times as much as the non-irradiated one. Convectional aging of the titanium alloy at 823 K leads to occurrence of an oxygen solid solution in titanium without essential increasing the wear resistance.

Introduction

Titanium and titanium alloys have been used extensively in aerospace, marine, and medicine industries. The only disadvantage which restricts their more widespread application at least in mechanical engineering is poor tribological properties [1]. The latter properties can be improved by applying various surface treatments. The diffusion treatments are particularly interesting, since they take advantage of the high reactivity of titanium with respect of carbon, nitrogen, and oxygen to produce high hardness surface layers well bonded to the matrix. Among the surface treatment techniques, the thermal oxidation and oxygenation are probably the much simplest ones. The higher is the surface temperature of a specimen the more efficient is the process of titanium oxidation and consequently the outer TiO_2 and inner diffusion layer formation. The solid solution significantly hardens the material and it is able to improve the wear resistance of titanium alloy components [2].

However, it is well known that the surface temperature in some cases reduces the fatigue strength of titanium alloys. This phenomenon undoubtedly takes place also during oxidation. Consequently, on one hand the high temperature of a specimen when oxidated is desirable for efficient diffusion of oxygen in titanium on another hand the temperature may be harmful for the lost of fatigue strength of titanium alloy components. Solution of the problem is in technique allowing an efficient oxygen absorption and diffusion in titanium at relatively low temperature. Enhancement of oxygen diffusion may be obtained by assistance with a simultaneous irradiation. The latter probably could be realized with a low-energy, high-current electron beam (LEHCEB) of microsecond duration. LEHCEB has been chosen for the enormous number of examples of its successful application in materials science in particular for enhancement of nitrogen diffusion in titanium at decreased temperatures [3].

Mainly the comparison between the aged and irradiated at aging temperature Ti-6Al-4V alloy was the aim of research carried out. Enhancing the wear resistance of Ti-6Al-4V alloy through electron beam assisted oxygenation was revealed.

Experimental

Samples were disks 4 mm thick and 18 mm in diameter. They were cut from the rod ingot of commercial Ti-6Al-4V alloy and subjected to a conventional mechanical polishing up to a surface roughness of 0.04 μm.

Different test techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD) analysis, Auger electron spectroscopy (AES) and wear tests were applied for investigation of the processed materials.

Two series of the specimens was irradiated by a LEHCEB in Ar plasma environment at a pressure of 0.03 Pa in the two modes: at ambient (300 K) and elevated (823 K) temperature, respectively. The electron-beam parameters were: 2.5—3.5 μs pulse duration, 30 keV maximum electron energy, 2.5 J/cm^2 beam energy density, and 0.1 Hz pulse repetition rate. Number of irradiation pulses was equal to 40. This electron beam allowed a surface melting of the sample being irradiated [4].

One more series of specimens was aged is such a way that the temperature profiles of aged and irradiated at elevated temperature specimens were close to each other. In fact, temperature profiles were coincident excepting short-time (~10^{-3} s) regular temperature discrepancies owing to heating of a specimen with a LEHCEB. The aging was performed in a vacuum at a pressure of $7x10^{-4}$ Pa.

Results and Discussion

AES element distribution profiles for non-treated, aged, and irradiated in two modes specimens showed that the virgin specimen consists of Ti, Al and V elements. As usual the chemical composition of the surface layer is different from the bulk. Namely, the surface layer contains oxygen and carbon which present permanently in a surface layer of any element or alloy. In many cases these two elements are non-desirable contaminants appearing at the surface by dissolving from the ambient atmosphere. Electron beam irradiation allows cleaning the surface layer from contaminants. In particular after 40 pulses initial 40-micron contaminated layer is purified from oxygen and its thickness is twofold less than that for non-treated specimen. The distribution profiles of the other elements after irradiation at ambient temperature are close to those for non-treated specimen.

It was established that oxygen distribution profiles after irradiation at ambient and elevated temperatures are quite different. The purification from oxygen in the first irradiation mode is changed to absorption of oxygen in the second one. Thickness of the diffusion layer increases and at the depths of 50 and 300 nm the concentration of oxygen equals to 10 and 6 at. %, respectively. The major role in oxygen absorption and diffusion belongs to the holding of a specimen at elevated temperature because irradiation without additional heating results in purification of the surface layer from oxygen.

The aged specimen similar to titanium alloy irradiated at elevated temperature absorbs oxygen. Nevertheless, absorption and diffusion of oxygen in aged specimen is less efficient than that in irradiated at elevated temperature one. Indeed, the thickness of a diffusion layer for aged specimen is about 200 nm and the concentration of oxygen at the depth of 50 nm equals to 5 at. % only.

It should be concluded that irradiation at elevated temperature enhances oxygen absorption and diffusion in titanium in comparison with diffusion at aging and, in contrast, irradiation at ambient temperature results in purification of titanium from oxygen.

XRD tests revealed that non-irradiated Ti-6Al-4V alloy consists of α and β-phases. Positions of peaks of these phases are shifted with respect of α and β titanium references towards the larges angles. The latter takes place owing to presence of alloying additions in titanium crystal lattices.

After irradiation at ambient temperature the broadening of α-phase peaks and its shifting towards the larger angles are observed. This is an evidence of formation of α'-phase and appearing of residual tensile stresses. Moreover, a splitting of the peak at angle $2\theta=63.6°$ takes place which is a clear evidence of α'' phase occurring. Formation of α' phase is accompanied by a weak hardening of titanium while a formation of α'' phase is accompanied by a softening of titanium.

Aging of titanium doesn't lead to the phase transitions of titanium. In virgin and aged specimens there are two phases of α and β titanium. The only event which takes place is narrowing of peaks of α-phase due to the relaxation of residual stresses in the surface layer of specimen.

The most interesting phase composition of titanium alloy is observed after irradiation of Ti-6Al-4V specimen at elevated temperature. First of all, it should be noticed a small broadening of α-phase peaks which is obviously occurred as a result of intensive oxygen absorption and diffusion. It is well known that oxygen is an α-stabilizing element which forms interstitial solid solution. A large fraction of oxygen dissolved in titanium lattice results in a high magnitude of intrinsic stresses which are evident as a broadening of α-phase peaks. These stresses do play a major role in phase transformation of β-phase. Reflex at angle $2\theta=57.6°$ is splitting into the two reflexes. One of them is β-phase peak and another one is ϖ-phase peak. In such a way $\beta \rightarrow \beta+\varpi$-phase transition took place and athermal ϖ-phase has occurred. It is interesting to notice that this phase doesn't occur at aging but simultaneous irradiation at aging results in the omega phase formation. Nevertheless, irradiation in the case given isn't the major reason for the omega phase formation. It just induces the phase transformation through saturation of titanium with oxygen. It has been demonstrated by *Paton* and *Williams* [5] that there is the marked effect of oxygen in lowering the temperature of $\beta \rightarrow \beta+\varpi$ phase transition.

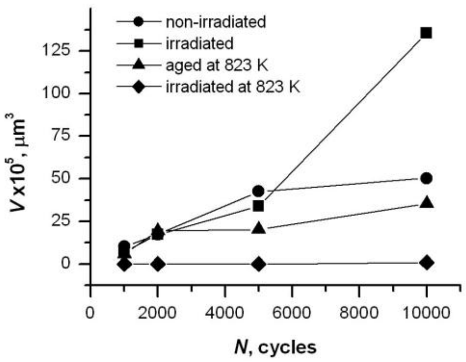

Fig. 1. Volume wear as a function of sliding distance for various treatment modes.

The tribological tests were performed for the untreated, aged, and irradiated at ambient and elevated temperature specimens. The results are presented in Fig. 1.

As it was described above the non-treated specimen has poor tribological properties including the wear resistance. Irradiation at ambient temperature results in even lowering of wear resistance in comparison with a virgin titanium alloy specimen that related to the occurrence of α'' martensite metastable phase of titanium. A formation of α'' phase is accompanied by a softening of titanium alloy, moreover, appearing of the residual tensile stresses is a factor which could lead to the surface microcracking and deterioration of wear resistance.

Aging of a specimen leads to a weak enhancing the wear resistance due to a strengthening effect of interstitial α-stabilizing atoms. Nevertheless, in comparison with a combined treatment including aging and irradiation this enhancing is negligible. Combined effect of hard ϖ phase and strengthening influence of interstitial atoms of oxygen led to a remarkable result. The wear resistance of titanium alloy irradiated in this mode is more than fifty times as much as the non-irradiated one.

References

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